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TECHNICAL REPORT
WVT-RI-6001-I

CHEMICAL MILLING

BY

C. H. ROSE

DECEMBER-1960

INDUSTRIAL PREPAREDNESS MEASURE 80304231-03-46400

WATERVLIET ARSENAL
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CHEMICAL MILLING

Abstract

A process study, outlining the capabilities and limitations of chemical milling, the materials for which it is suitable, the accuracies and surface finishes expected; derived from a study of the available literature and visits to users of the process, are made to determine the applicability of the method to the pilot production requirements of Watervliet Arsenal.

Forty-two pounds of 4340 steel were removed from a 90mm M41 breech ring in 61 hours by chemical milling. Surface finish was 62 microinches. Metal removal rate was .0007 inch per minute.

Cross-Reference Data

Chemical Milling
Milling, Chemical
Etching, Precision
Materials, Ultra-hard, milling
Manufacturing Processes

Do Not Remove This Abstract From The Report

CONCLUSIONS

Chemical milling is a low cost method of metal removal under certain conditions.

Since the rate of metal removal is low, in terms of inches per minute penetration, many parts must be processed simultaneously in order to obtain low costs. Either batch or continuous moving type facilities can be used, depending on the length of exposure required.

The cost of the facility is usually lower than the cost of equivalent cutting machine tools. However, an area separate from machine tools is recommended because of the corrosion problems that could arise. An exhaust system with hoods over the tanks is required.

Surface finishes tend to improve or deteriorate from initial conditions toward a middle class with continued exposure, usually around 60 to 100 microinches, but are dependent in part on the material used.

No residual stresses are induced by chemical milling, as may be by some machining operations.

No deleterious effects on fatigue strength have been noted beyond those normally associated with a given geometry and surface finish. It would seem, however, that stress-corrosion effects might occur in parts etched under high residual stresses, such as those resulting from heat treatment.

Small amounts of material may be more readily removed by this method than by grinding. Slightly oversized parts may be sized without appreciable change in surface finish and without the care in locating and fixturing required for grinding.

Difficult geometries may be produced by this process. Recesses, undercuts, tapers, etc., can be etched by the use of careful masking methods.

Some materials, very difficult to machine, can be conveniently shaped by chemical erosion. Each individual case must be considered before a decision can be made on the feasibility and probable cost of producing a particular geometry from a specific material.

OBJECTIVE

The objective is to delineate the capabilities and limitations of the chemical milling process, based on a study of available literature and on visits to users of the process, in order to determine the possible applications to the pilot production requirements of Watervliet Arsenal.

INTRODUCTION

Chemical milling is the precision contouring of metal into any size, shape or form without the use of physical force, by a controlled chemical reaction.

Chemical milling has no parallel in industry. It is so new and offers such a wide and unique advantage that it permits the employment of entirely new design concepts. For that reason, savings in time and money can be frequently achieved. Designers can now call for the chemical milling of parts after forming and heat treating, or eliminate detailed sub-assembly parts by designing intricately formed stiffeners. They can avoid warpage caused by heat of cutting tools, and can chemically mill both sides of a part simultaneously. Also, it is possible to chemically mill thinner and larger sheet stock than would be practical to machine. Chemical milling offers virtually unlimited scope for engineering and design ingenuity. To gain the most from its unique characteristics, chemical milling should be approached with the idea that this new industrial tool can do jobs not practical or possible with any other metal working methods.

By 1956, the problems associated with the chemical milling of aluminum alloys had mainly been solved. Some work was done on alloy steel and titanium alloys as early as 1955, but subsequent investigations were greatly complicated both by the nature and diversity of the materials which were already adopted for certain purposes or were the subject of serious consideration.

Workable methods have now been established for applying chemical milling to practically all these materials. The greatest difficulty has been experienced with the cobalt nickel alloys, but these are now yielding to the research effort. The practicability of producing elaborate shapes from materials that are extremely difficult to machine by other methods will depend upon the effective exploitation of these new techniques. Chemical machining will likely prove to be of considerable value in the solution of problems that are constantly arising as the result of the introduction of new materials.

The difficulties of many production departments have already been greatly increased by components of growing complexity. These are frequently conditions. Line definitions of ± 1/32 inch are readily obtained.

SURFACE FINISH

The original surface affects the finish obtained on chemically milled surfaces. In the early stages of chemical milling, original surfaces were reproduced by chemical milling and could not be improved. However, the chemical industry has developed etchants, being used currently on production items, that improve the surface finish on a great number of alloys. The amount of improvement depends on the properties of the alloy itself. Surface finishes that are being obtained on production runs are listed below:

1. Aluminum Alloys -

Finishes of 125 RMS or better are obtained on good stock. In cases where the original surface finish is very poor, a finish no rougher than 250 RMS can be obtained.

2. Magnesium Alloys -

Exceptionally smooth surface finishes of 80 RMS or better are being consistently obtained. Surface imperfections can be "washed out" to a great extent.

3. Titanium Alloys -

Mirror-like finishes in the range of 40 RMS or better are readily achieved. Grooves and surface ridges tend to "wash out".

4. Steel Alloys -

Excellent surface finishes are attainable currently on cuts of 1/4 inch or less. For example, a finish of 60 RMS is readily obtained on 4130. On deeper cuts, the surface finish will depend on the granular structure of the alloy.

METALS THAT HAVE BEEN CHEMICALLY MILLED

A partial list of materials successfully chemically milled includes steel, stainless steel, titanium, magnesium and mag-thorium, as well as aluminum. Specific alloys of these metals that have been etched are tabulated in figure 1.

Material	Alloys	
Aluminum	2024	7178
	2014	1100
	5052	7079
	6061	DTM 646
	7075	
Magnesium	AZ31B (FS 1)	AZ91A
	HK31	AZ63
	HM21	ZK51
	ZK60A	EZ33
Titanium	A-110AT	C-110M
	C-130AM	A-70
Steel	17-7	A286
	17-4	Inconel X
	AM 350	Inconel
	304	Monel
	316	K Monel
	321	Inconel 702
	347	Incoloy annealed HH
	4130	Nimonic 75 annealed
	4340	Nickel annealed
	Hi-Tuf	

Figure 1. Tabulation of metals that have been chemically milled.

ADVANTAGES OF CHEMICAL MILLING

Chemical milling affords numerous advantages over machine milling which fall into two main classifications: (1) engineering design advantages, resulting in lighter-weight construction, and (2) production and economic advantages, usually resulting in lower cost per part.

Engineering Design Advantages

1. Etching after Forming

The process can be performed after forming operations while machine milling is usually limited to flat or slightly contoured parts. Forming to exact contours is extremely difficult after machining.

2. No Machining Restrictions

The process is not limited as is machining in regard to shape, direction of cut, and radius of cutters. Complex shapes, broad or narrow cuts, and comparatively sharp corners are possible in one operation by the chemical milling process.

3. Application to Complex Contours

The chemical milling process can be applied to complex shapes or formed parts to remove simultaneously metal from both surfaces of a sheet. This avoids warpage that results from the inability to machine simultaneously both sides of a sheet.

4. Lighter Construction

The process permits design, not possible by other means, of lighter weight construction through integrally stiffened structures. This design eliminates many fittings, stiffeners, or doublers and fasteners. Web or waffle type of sandwich construction appears more feasible by chemical milling than by machining, because lands can easily be left on a panel wherever necessary.

5. Tolerances

Thickness tolerances can be held by the process with no special holding fixtures necessary.

6. Weight Reduction

Chemical milling permits reduction in weight of parts, such as extrusions, forgings and deep-drawn parts, which would otherwise be heavier because of minimum-thickness limitations required for forming these parts.

7. Tapering

The process permits tapering of sheets, extrusions, hat sections, and other parts such as stiffeners, to transfer design stresses proportionally.

8. Integral Stiffeners

Bands or stiffeners can be produced integrally with the skin and may be curved or contoured so as to direct the transfer of stresses as desired.

9. Step-Milling

Various depths of cut may be performed by steps on large areas of one sheet by progressive unmasking.

While all basic principles still apply when designing for chemical milling, it may be assumed from the above that, to utilize this process to its fullest, entirely new design concepts may have to be employed.

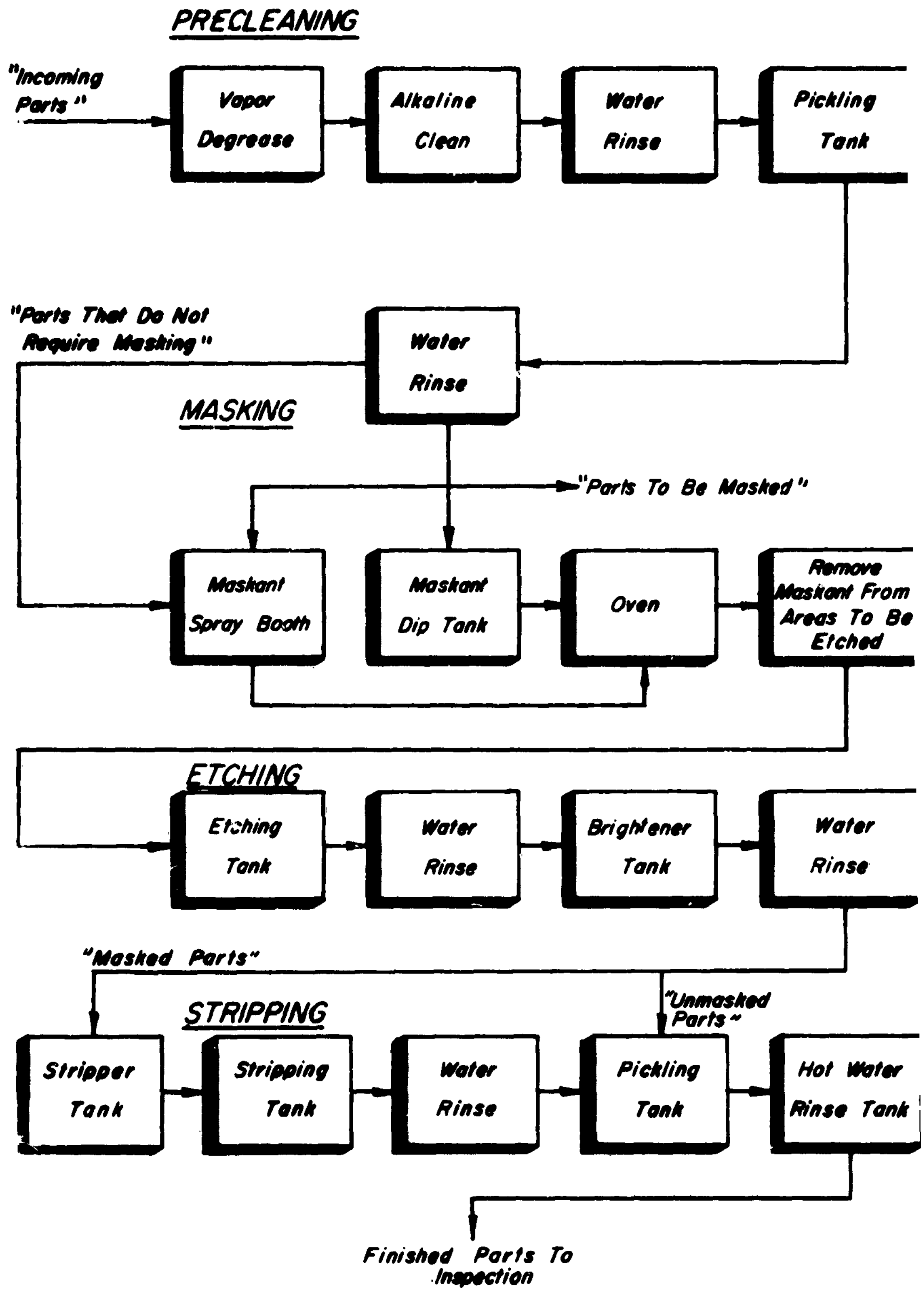


Figure 2. Chemical milling process flow sheet

Production and Economic Advantages

1. No Highly Skilled Operators Required

The process lends itself to automation by electronic instrumentation.

2. Economy of Production

The number of parts that can be etched simultaneously is limited only by the size of the tank and the size and shape of the parts, thus offering tremendous manufacturing advantages. However, parts that must be held to a close thickness tolerance can be etched only one at a time.

3. No Sanding or Polishing Required

Chemical milling parts require no further work, such as sanding or polishing, to improve surface finish. Following machine-milling of thin skin sections, a hand-polishing operation with rotary or vibrating sanders is sometimes necessary to improve surface finish.

4. Conventional Equipment

Equipment required for the chemical milling process is of the conventional cleaning and pickling type, some of which is already available in standard sizes for metal cleaning. A process flow sheet is shown in figure 2.

PROCESS CHARACTERISTICS

Etching is uniform at any point of the unmasked area, and the radius at the edge equals the depth of etch. See figure 3.

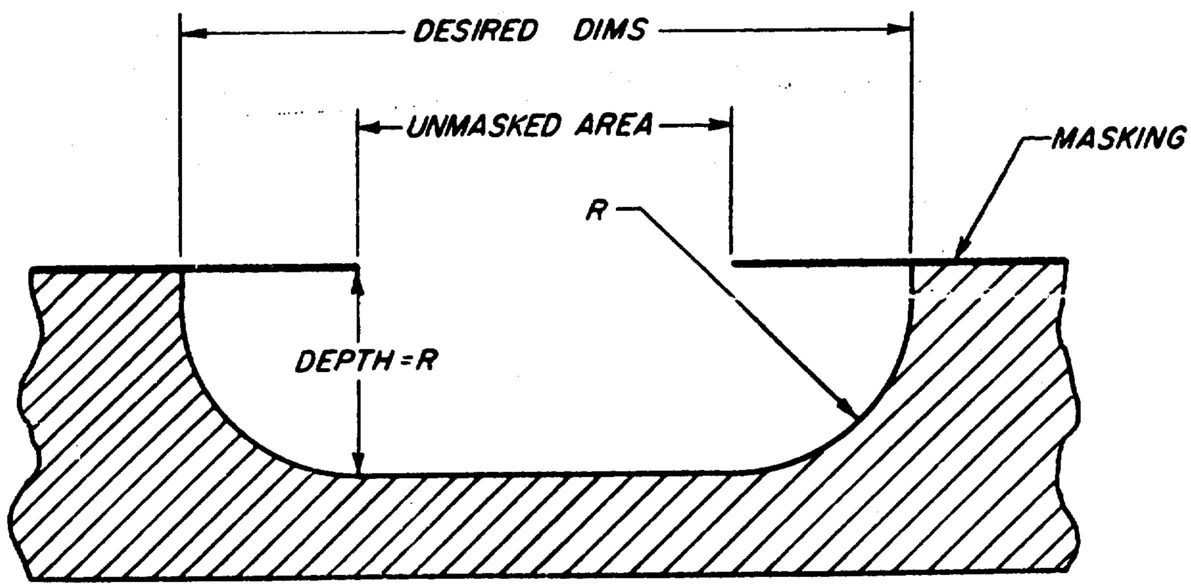


Figure 3. Cross-section showing normal undercut occurring on a masked chemically milled part.

When masking materials are used in the etching of parts, the depth of cut is limited, in most cases, to 0.5 inch maximum. This limitation arises from the fact that gas is trapped underneath the mask. The chemically milled surface will be uneven if the gas cannot be displaced by agitation of the solution. However, this limitation can sometimes be overcome by the mechanical movement of the parts.

MECHANICAL PROPERTIES OF ETCHED MATERIALS

The physical and mechanical properties of the etched sheet are practically the same as those of the sanded and polished machine-milled sheet. Etching of various kinds of metal parts has been carried on for many years without known detrimental effects, for example, cleaning, enhancing of crystalline structure for specimen examination, and decorative purposes. This would indicate that there is no reason to suspect that the chemical, physical, or mechanical properties would be altered. Results of tests made to date confirm this indication.

Careful microscopic examination of chemically milled parts shows that there is no chemical attack between grain boundaries of the surface and no change in composition of the surface. However, the possibility of stress corrosion effects in parts containing appreciable residual stresses must be considered.

MASKING

There are various methods of obtaining selective etching by masking, two of which are briefly discussed below.

1. Masking by Spray, Dip or Brush Application of Chemically Resistant Organic Coatings

Selective protection can be obtained by first covering the entire surface of the part by spraying, dipping, or brushing with specially formulated coatings. A template is then applied to the area to be etched and the maskant is scribed through and removed before etching. Stiffeners hold thin sections of the template from moving while the maskant is being scribed, thus maintaining the required close tolerances.

2. Silk Screen Method of Applying Maskant

When complex patterns or configurations involving extremely fine details are required, the silk screen method of applying maskant is used. In this process, a maskant is used that can be applied through the small openings in a silk screen, and on areas where no masking is required (areas to be etched), the openings in the silk screen are covered with a nonporous material to prevent the maskant from penetrating through the silk screen.

After the part has been etched, the maskant is removed by a special stripping solution.

COST COMPARISONS

Cost comparisons between chemical milling and machine-milling in many cases show considerable savings by using chemical milling. Such cost comparisons have been difficult to evaluate because they were calculated only for etched parts that could be duplicated by machine-milling. Many parts can be made only by erosion and, for these, no cost comparison can be made.

As more parts are produced by the chemical process and as technical improvements are made in the process, the cost of fabrication will continue to decrease. There are other advantages not readily evaluated in dollars and cents, such as simplified and lighter weight construction and improved quality of product.

The most economical operation is realized for parts that require no masking. For example, some forgings, extrusions, and drawn parts requiring thicker sections for ease of manufacturing can be reduced in weight simply by etching.

Forgings having large web areas in the forging plane that cannot be forged to minimum design thicknesses, may be readily etched to the desired dimension. The amount of metal to be etched must be added to the overall forging dimension to eliminate masking. However, a cost evaluation should be made on both methods (no masking vs. partial masking).

Many extrusions are heavier than necessary because of limitations in extruding thin sections. The thickness of these sections can be reduced simply by immersion in the etching solution for the required time, or if desired, they can be tapered.

Drawn parts are more readily made from heavier material which is subsequently etched to the desired thickness. Etching proceeds uniformly in all directions and at the same rate in both stressed and unstressed areas; therefore, portions thinned due to drawing should be given consideration in design.

Tubing, to be fusion welded to an end fitting or another tube, may be etched outside or inside, except for a short distance from the end to be welded to compensate for the weld factor.

Full advantage of weight reduction may be taken on panels with varying stress patterns. Web areas with four, or even more, different thicknesses are practical to produce by the process, using the step-masking technique.

CHEMICAL MILLING OF CASTINGS

New chemical milling techniques achieve the same high quality results on castings as have been so successfully obtained in the past on sheets, extrusions, and forgings. Of interest to both the designer and the foundryman, these new developments in the state of the chemical milling art now make it possible to produce better designed castings than have previously been available.

1. Thicknesses Determined by Casting Process

Ideally, structural requirements should be used to determine section thicknesses when designing castings where weight is an important factor. On the other hand, one of the basic foundry rules is that all sections of a casting should be as nearly uniform in thickness as possible to prevent such common casting defects; as hot tears and casting strains, except that inner sections of a casting must sometimes be made thinner than outer sections to provide proper cooling after the metal has been poured into a mold.

Since chemical milling acts on any desired surface regardless of shape or location, the designer can accurately calculate the structural requirements of the finished part first, and then add the necessary metal to make it a good sound casting. The foundry man no longer has to compromise between good foundry practice and the desire to produce the lightest, strongest part possible. After casting, all excess metal can be removed by chemical milling. Metal removal can be "overall", or be restricted to selected areas only.

2. Overall Reduction

Overall reduction was the first application of chemical milling. Here, the entire part is exposed to the chemical solutions, so that all dimensions are reduced by exactly the same amount. In this case, it may be necessary to increase certain dimensions on a casting so that following the overall reduction, every section will have the proper dimensions.

3. Controlled Area Reduction

Controlled area chemical milling is accomplished by covering certain areas of a casting with a protective coating of maskant. In this way, the chemical action is restricted to those areas that are not coated. This eliminates the need to cast additional weight into sections that do not require it for ease of casting. Instead, these sections are cast to the proper dimensions since the maskant will prevent the surfaces in the protected areas from being altered in chemical milling.

4. Surface Finishes

Surface finishes are generally improved by chemical milling.

However, the surface improvement depends in part on the porosity of the casting and upon the alloying constituents. Finishes on aluminum castings, for example, depend on the silica content. The "as cast" finish is usually fairly rough; however, after chemical milling, finishes are usually 250 RMS or better.

Surfaces of steel castings are improved also, and are in the neighborhood of 125 RMS depending on the original surface finish.

The resulting finish, in every case, will depend to a great extent on the casting process used. In addition, finishes will depend, to some extent, on the individual part and the depth of cut.

EXPERIMENTAL CHEMICAL MILLING OF 90MM BREECH RING CASTING

Materials and Apparatus

1. Special masking paint - type U.S.C.M. #607*
2. Lead tape
3. Special descaling solution
4. U.S.C.M. etchant #310*
5. Commercial pickling solution
6. Rust preventive
7. Stainless steel tank, cables and hoists for containing etchant, supporting part, etc.
8. 90mm M-41 breech ring

*U.S.C.M. - United States Chemical Milling Company

Method of Procedure

The operational procedure consisted of the following:

1. Layout of Breech Ring - It was necessary to lay out the final dimensions from all center lines to accurately determine the size of the rough casting, to establish the amounts of material to be removed from various areas.

2. Masking of Breech Ring - Since the stock distribution was not exactly equal, several areas had to be protected from the etchant during part of the chemical milling operation. To afford protection at the required points, a special paint type maskant, which was developed by the United States Chemical Milling Company and designated as USCM #607, was used. Six coats of this material were applied allowing 30 minutes drying time between each application. Two layers of a special adhesive type lead tape were applied for additional protection during actual chemical milling.

3. Weighing - The component was weighed prior to chemical milling to

determine the total weight removed from the breech ring. Before chemical milling, the weight was determined to be 810 pounds.

4. Descaling - The entire breech ring casting was then rigged with a stainless steel cable and suspended in a commercial descaling solution for several 10 minute periods to completely remove all the scale from the breech ring casting. It is essential that the scale be removed to insure the uniform chemical milling of the part. It should be noted that sand blasting would accomplish this scale removal at a considerably lower cost. However, since the company performing this work had no adequate sand blasting equipment available, the descale solution was utilized.

5. Chemical Milling - Since breech rings are a modified 4340 steel, a special steel etchant developed by the United States Chemical Milling Company, designated as USMC Etchant #310, was selected. The component was suspended in the stainless steel tank, the sides of which were ventilated by a blower to remove the toxic fumes which are generated during the chemical milling process. Although the temperature of the etchant material should be approximately 150°F, it was decided to initiate etching at 118°F since the large amount of metal being removed would develop heat through chemical reaction. The rate of stock removal, time and temperature follow:

Time	Solution Temperature	Stock Removal - Inches per Minute
1st hour	118°F	.0006
2nd hour	150°F	.0005
3rd hour	140°F	.00075
4th hour	147°F	.00075
5th hour	147°F	.0007

The original estimate of stock to be removed averaged .250 depth from the unmasked surfaces; however, the stock removal appeared so well controlled that it was decided to remove the remaining .015 to finish milling the outside of the ring to size. Several problems were encountered during the actual milling of the breech ring. Several gas striations were apparent after processing. However, a schedule of rotation would eliminate this problem. It was also noted that maskant USCM #600 would be satisfactory and would not require the lead taping used with maskant #607. A more complete set of measuring instruments should also be available for checking finished sizes. Since the only measuring instrument available that would measure dimensions in excess of 7" was a 24" scale, the accuracy possible was ± .010 inch.

6. Cleaning - Since some smutting occurs during the removal of large quantities of material and since all evidence of the etchant must be removed, the breech ring was rinsed in clear water, cleaned in a pickling solution to de-smut the ring and then rinsed in clear water.

7. De-Masking - The maskant was removed from the breech ring prior to inspection and preservation. At the time, it was again noted that USCM-600, a more easily applied and removed maskant, would have been equally effective.

8. Protecting - Since this component would be in transit for a prolonged period, a commercial rust preventive solution was applied.

9. Weight - The weight of the breech ring at this time was 768 pounds, indicating that 42 pounds of metal had been removed.

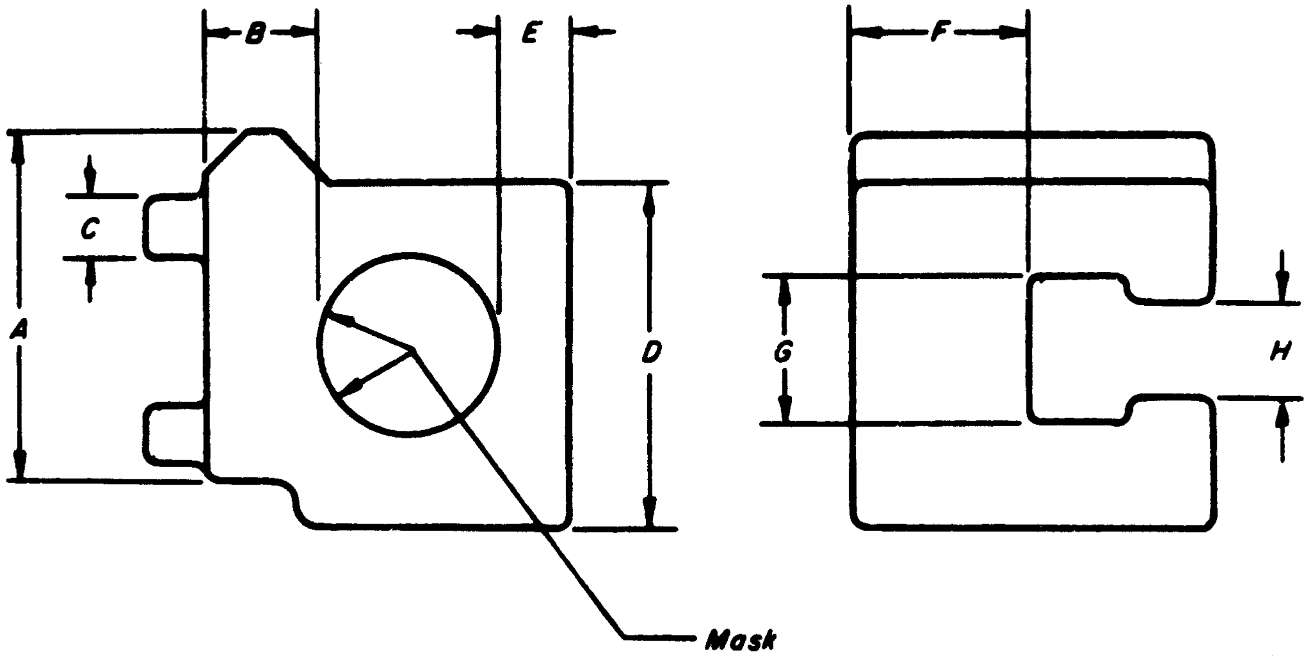
Inspection

Upon receipt of the breech ring at Watervliet Arsenal, an accurate layout was made. It was noted that although most external dimensions were within or slightly over drawing specifications, several were slightly below drawing specifications in some areas. The reason for this was:

1. Lack of adequate measuring instruments.

2. Inability of the chemical milling process to correct "out of square" or parallel conditions without excessive masking.

A diagram and table of the amount of material removed, surfaces masked, distributed stock and overall percentages, are shown in figure 4.



	A	B	C	D	E	F	G	H
Before Chemical Milling	16.250	3.100	3.350	15.430	3.608	8.350	6.400	4.806
After Chemical Milling	15.740	2.825	2.875	14.850	3.152	7.825	5.900	4.300
Over-all Removal	.510	.275	.475	.580	.456	.525	.500	.506
Removal Per Side	.255	.275	.238	.290	.228	.262	.250	.253

Figure 4. Diagram of a chemically milled breech ring with accompanying table of milled dimensions

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